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A SCANNING SPECTROPHOTOMETER FOR READING THIN-FILM DOSIMETERS

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Abstract

It is possible to convert a conventional spectrophotometer into a versatile scanning spectrophotometer, without great difficulty or expense. The improved instrument can be tailored to perform many electro-optical tasks by the appropriate arrangement of modular components. In this work, basic optical components (light sources, monochromator, and sample chamber) of a conventional spectrophotometer were used on an optical bench. Specially designed accessories could be added to these components in order to measure at given wavelengths (from 200 to 800 nm) spatial variation (down to less than 10 μm) of optical transmission or reflection quantities in thin-film dosimeters, over a wide dynamic range. For high-speed data acquisition, analogue-to-digital conversion could be programmed to give tabular or graphical absorbed dose readings from calibrated film as a function of optical or spatial variables.

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1. Introduction

The use of films and papers that change colour or shade when exposed to ionizing radiation is a promising dosimetric technique.

Such dosimeters, mainly in the form of thin radiochromic dye films, have been used at the Risö Accelerator Department to determine the beam characteristics and dose distributions from the department's 2 MeV and 400 keV electron accelerators[1]. In order to analyse the spatial dose distribution as indicated radiographically by an individual film, light measuring equipment having scanning capability, high optical resolution, and short reaction time is required. Such equipment is commercially available, but the price of a typical high-quality isodensity tracer or microdensitometer is relatively high. Moreover, these instruments are not precisely suited to the varied needs of dosimeter film analysis. Therefore it was decided to modify a Zeiss PMQ II spectrophotometer already in use in the laboratory. The spatial resolution of photometric analysis provided by this instrument first had to be improved. Following this a number of further improvements were introduced in order to achieve shorter rise time, greater sensitivity, and more versatile read-out possibilities.

2. Instrument details (see figure 1 giving a block diagram of the apparatus).

2.1. Optical improvements

2.1.1. Transmission measurements

The optical resolution of the system is determined primarily by the size of the analysing light beam as it scans the film to be measured photometrically. Before improvement the cross section of this light beam in the basic instrument was 2 x 15 mm, as formed by a lens system in the attachment already provided. The aim of the improvement was to lower the effective analytical cross section by as much as a factor of 200.

Only rather modest improvements were needed to enhance the optical resolution of the PMQ II spectrophotometer. The image of the adjustable slit on the output side of the monochromator was projected onto the film by means of a lens situated so that the effective slit size was reduced by a factor of 10. The slit could be adjusted between 0 and 2 mm; accordingly the effective scanning slit widths were variable between 0 and 0.2 mm. The effective slit length was fixed at 0.5 mm. In normal use the slit was not opened wider than 0.1 mm, and thus the effective slit width was always equal to or less than 10 μm.

The lens was a camera lens corrected for spherical and chromatic aberration, with focal length f = 25 mm and numerical aperture 1:1.4. Its range position was used to make fine adjustment of the focus. The aperture adjustment acted as a manual shutter. Circular black metal baffles were placed as close to the film as possible (see fig. 3), in order to restrict flare illumination from the lens[3] and sample-to-lens reflections.

It was also possible to replace the variable exit slit with a fixed slit so that the slit image on the film was constant in size, while the input light amount could be adjusted by the monochromator's variable input slit. In this arrangement, three interchangeable slit widths were selected for experimental use: 0.1 mm, 0.3 mm, and 1.0 mm, all with a length of 5 mm. This resulted in a change of the spectral band width of the system as determined by the slit arrangement[2]. Using a sodium lamp as light source, the band width at 590 nm was found to be 6 nm using the 0.1 mm slit.

With this set up, the original photodetector and amplifier supplied with the PMQ II spectrophotometer could be used to analyse films in terms of percent transmittance, percent reflectance, or optical density. Figure 2 is a photographic view of the optical portion of the instrument. Figure 3 is an illustration of the optical path from the light source through the

film samples to the photodetector.

2.1.2. Reflection measurements

The housing of the fluorescence attachment (ZFM 4) supplied with the PMQ II system was adapted for making reflection measurements. The set-up recommended by the manufacturer for measuring spectral dispersion of the photoexciting radiation was used. The cell holder that is normally used to hold the photoluminescent samples was tilted so that both the light input angle and the measuring angle are 45°. Figure 4 shows the incident and reflected light paths. The light spot size was approximately 2 x 5 mm. No effort was made to reduce its size, since high-resolution optical reflection measurements were not being made by opaque dosimeter systems. The same photodetector and amplifier were used for both transmission and reflection measurements.

2.2. Rise time

The nominal rise time for the PMQ II spectrophotometer is specified to be about one second, which would require the optical scanning to be extremely slow to be able to make useful photometric measurements of light changes occurring over small distances. The rise time could be shortened by chopping the light beam with a higher periodicity, as the rise time depends on the light chopper frequency. The rotating chopper[+] that was used made it possible to achieve a rise time of 10 milliseconds. For measuring very noisy or grainy samples this could be raised in four steps up to one second by inserting electronic filters.

A reference signal of the same frequency as the analysing signal was added for monitoring the final detection of the signal[4]. It is provided by a small lamp and a photodiode mounted at the chopper.

[+] a 2700 rpm motor with a cut disk giving a chopper frequency of 810 hz.

2.3. New amplifier and photomultiplier housing

While the above changes were incorporated directly into the existing spectrophotometric system, the need to measure percent transmittance as low as 0.01% (optical densities up to 4) necessitated an improved photodetector sensitivity without excessive electrical or mechanical noise. The following measures were taken:

a. An improved photomultiplier housing with a shorter light path and a light guide was installed. The total light collection angle was approximately 110° (see figure 3).

b. Both lamp and photomultiplier were provided with stabilized power supplies.

c. A preamplifier consisting of a voltage follower was mounted close to the anode of the photomultiplier.

d. A new amplifier with 80 dB amplification was constructed. The amplification could be varied in steps of 20 dB down to 20 dB. The amplifier was provided with a phase sensitive detector using field-effect transistors to obtain good liniarity. The amplifier also had an overload warning to make sure that it is always operated in its most linear mode.

2.4. Logarithmic amplifier

The direct output from the amplifier could be calibrated in terms of transmission fraction (transmittance T) or reflection fraction (reflectance R), but since the radiation absorbed dose determined by the colour change produced in the dosimeter was proportional to the change in optical density at a given light wavelength, it was the optical density that normally was measured. The optical transmission density is defined as

$$A_T = \log_{10} (1/T) = -\log_{10} T$$

where $T = \frac{I_T}{I_o}$, I_T being the transmitted flux density and I_o the incident flux density.

Similarly, the optical reflection density is defined as

$$A_R = \log_{10} (1/R) = -\log_{10} R$$

where $R = \frac{I_R}{I_o}$, I_R being the reflected flux density.

A logarithmic amplifier was constructed of commercially available circuit blocks and was built into the amplifier, so that A_T and A_R could be measured directly. The output from the amplifier was linear up to about A = 2.

2.5. Sample drive system

A synchronous motor attached to the sample stage enabled a row of samples to be driven through the light beam at a constant rate. The speed was variable in 10 steps from 5 mm/sec to 5 μm/sec. The drive system provided analog signal and digital signalling for registering of the position of the sample to a recorder and to a punched tape driver.

2.6. Recording of results

Different recording modes were provided. The transmittance T, reflectance R, optical transmission density A_T, or optical reflection density A_R could be registered on a galvanometer or an oscilloscope, or they could be plotted on a strip-chart recorder or an x-y recorder. It was also possible through a digital voltmeter and a paper tape puncher to store transmittance or reflectance data on a punched tape. When properly programmed, a computer

could carry out a series of dose calculations from the recorded photometric data, as long as thickness variations in the film material were negligible or were monitored simultaneously.

It was also possible for the computer to plot the optical density as a function of distance along the film plane, and thus eliminate errors introduced by the logarithmic amplifier at A higher than two.

3. Instrumental performance

3.1. Linearity

The linearity of the response of the instrument was checked by measuring the transmittance, T, of a calibrated photographic step tablet, and by converting these measured values to optical density, $A_T = -\log_{10} T$, and plotting these optical density values against the calibration values as supplied by the U.S. National Bureau of Standards. This plot is shown in figure 5 along with a similar plot made by using the logarithmic amplifier to measure optical density directly. The transmittance readings converted by computation to optical density values, show a linear relationship to within 2 percent up to A = 3.05, the maximum optical density level supplied by the step tablet. The latter curve shows that direct optical density readings are valid only to approximately $A_T = 2$.

The step tablet was calibrated in terms of "diffuse optical density"[5], which means that the light collection angle should be 180° and the light input angle should be close to 0°. Neither of these specifications was met in the new instrument, where the light collection angle was 110° and the light input angle was as high as 35°. Therefore a departure from the ideal curve (at a 45° angle on the plot in figure 5) should be expected. Since the instrument, with its relatively small slit width, was not designed to measure relatively turbid samples, such as photometrically calibrated photo-

graphic step tablets[7], the linearity curve of measured optical density versus true optical density was not an adequate means of calibrating the instrument. It was, on the other hand, suitable for checking the repeatability of the instrument, which was found to be better than 1%.

When the variable exit slit was used the slope of the curve was found to decrease by only approximately 1% in changing the slit from 0.08 mm to 0.2 mm.

3.2. Acutance

The scanning instrument's ability to measure abrupt spatial changes in the optical density of a high resolution radiochromic dye dosimeter could be checked by measuring across a knife-edge image registered on the film. A measure of that ability could then be expressed by the "acutance"[6], which was calculated by the relation:

$$\text{Acutance} = \frac{\sum_{i=1}^{n} (\Delta D/\Delta x)_i^2}{(D_B - D_A) \cdot n}$$

where $(\Delta D/\Delta x)_i$ = optical density change per corresponding scan distance for each of n equally spaced scan distances between D_A and D_B.

D_A, D_B = optical density at points on the knife-edge scan where $\Delta D/\Delta x$ is 0.005 $(\mu m)^{-1}$.

The optical density scan is shown in figure 6. It was made with 595 nm light, and the effective slit image size was 10 μm x 500 μm.

With n = 10, the acutance was calculated to be 5×10^{-4} $(\mu m)^{-2}$, which is a factor of nearly 10 lower than for a highly sophisticated and expensive scanning microdensitometer[7], but good enough for our purposes.

3.3. Measurements

The instrument has been used to analyse new types of thin dye films and to measure dose distributions by means of optical density measurements of high-resolution radiographic images recorded by commercial films. Typical read-outs are shown in figures 7 and 8, where transmittance and optical density have been plotted against distance by the x-y recorder, and in figure 9, which is a computer-printed plot of the optical density versus distance across beam spot images. The measurements were made using a light wavelength of 600 nm and a fixed slit size of 0.1 x 5 mm (effective size 10 μm x 500 μm).

4. Features of the instrument

a. Continuous adjustment of wavelengths from 200 to 800 nm.

b. Possibility of using either continuously variable effective scanning aperture or fixed effective scanning aperture at 3 dimensions: 0.01 mm, 0.03 mm and 0.1 mm.

c. Rise time of the output signal adjustable in 4 steps from 10 msec to 1 sec.

d. Simple conversion of photometric readings by means of linear or logarithmic amplification.

e. Wide variability and ease of alternating or simultaneous read-out: strip-chart recorder, x-y recorder, electrometer, galvanometer, digital, punched paper tape, oscilloscope, etc.

f. Variable speeds over a range of 1 to 1000 in the sample drive system.

g. Optical reflection, transmission, or luminescence capabilities.

h. Light collection capability between specular and nearly diffuse optical conditions (so that one can intercompare with either spectrophotometer or densitometer readings).

Some of these features are also attainable in more expensive micro-densitometers, but it must be emphasized that this instrument was custom-made in a relatively inexpensive design based on an existing photometric system to perform specialized tasks for handling radiation dosimeter films and high-resolution radiographic imaging systems.

5. Acknowledgements

Thanks are due to E. Engholm Larsen, who constructed all the mechanical and electrical parts needed for the changes of the spectrophotometer.

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6. F.H. Perrin, "The Structure of the Developed Image", Chapter 23 in ibid.

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Figure Legends

Figure 1. Block diagram of the apparatus.

Figure 2. Photographic view of the optical portion of the instrument in the transmission mode.

Figure 3. Diagram of the optical path in the transmission mode.

Figure 4. Diagram of the optical path in the reflection mode.

Figure 5. Calibration curves of optical density measurements of standard density step tablet.

Figure 6. Spatial optical density scan across a knife-edge image on a radiochromic dye film (measured at 595 nm wavelength).

Figure 7. Typical scan recording of optical transmittance (at 600 nm) across a radiochromic dye film image produced by collimated electron beam irradiation (using x-y recorder).

Figure 8. Typical scan recording of spectral optical density (at 600 nm) across a radiochromic dye film image produced by collimated electron beam irradiation (using x-y recorder).

Figure 9. Typical scan recording of spectral optical density (at 600 nm), across a radiochromic dye film image produced by collimated electron beam irradiation (using computer read-out and printing).

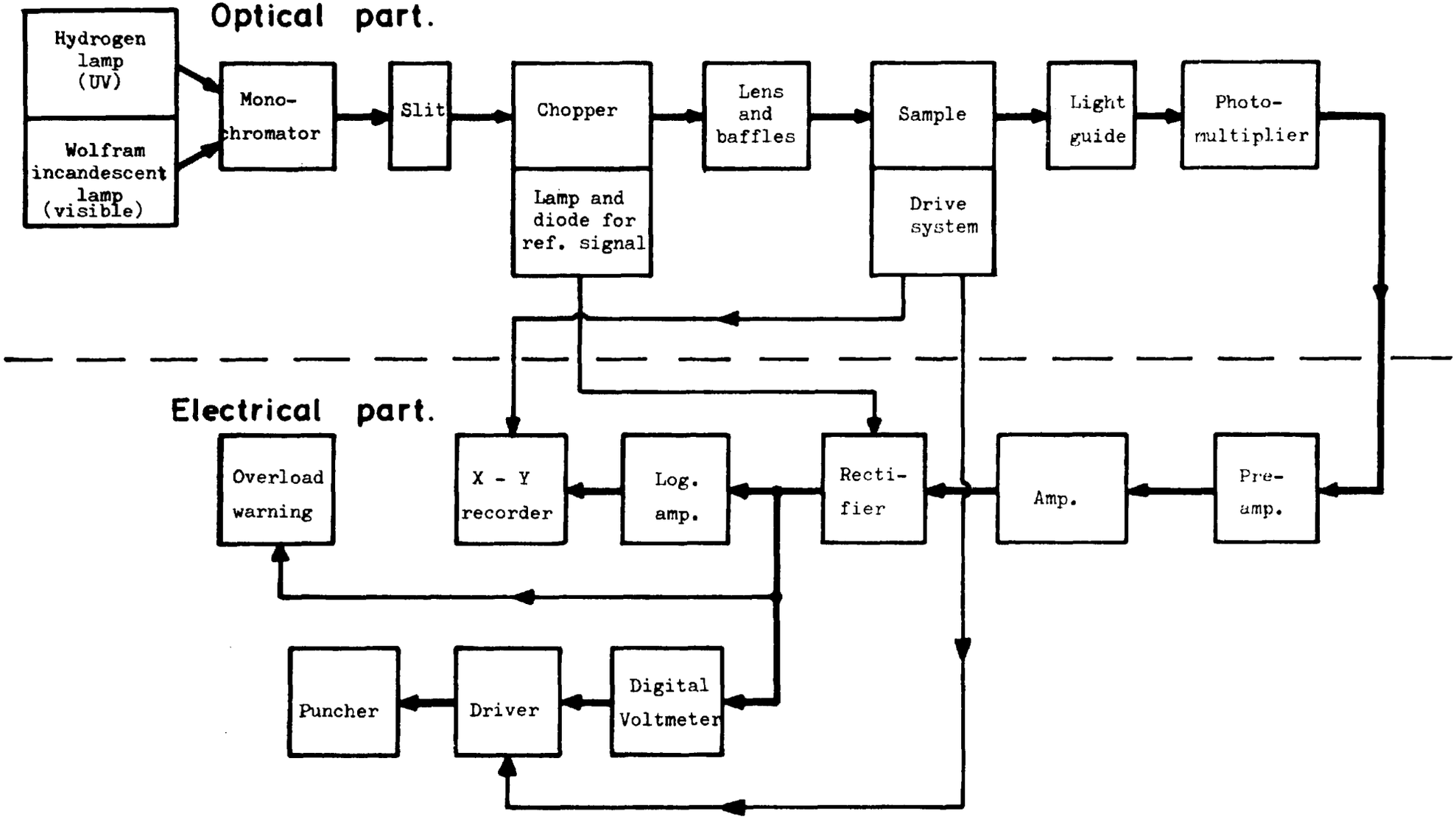
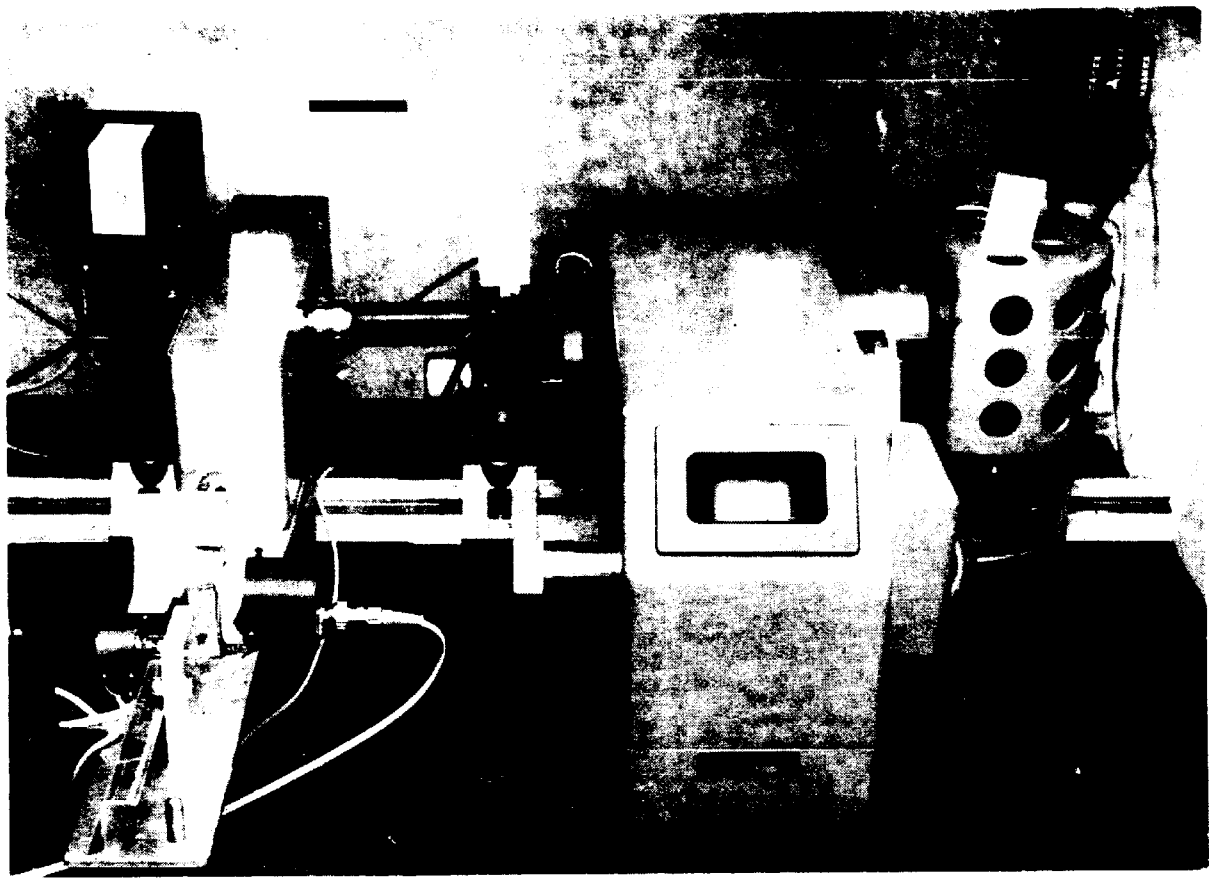


Fig. 1 Scanning spectrophotometer. (Block diagram)



1. Lamp housing.
2. Monochromator.
3. Chopper with lamp and photodiode for reference signal.
4. Sample drive system.
5. Sample house with camera lens.
6. Photomultiplier housing.

Fig. 2 Photographic view of the optical portion of the instrument in the transmission mode.

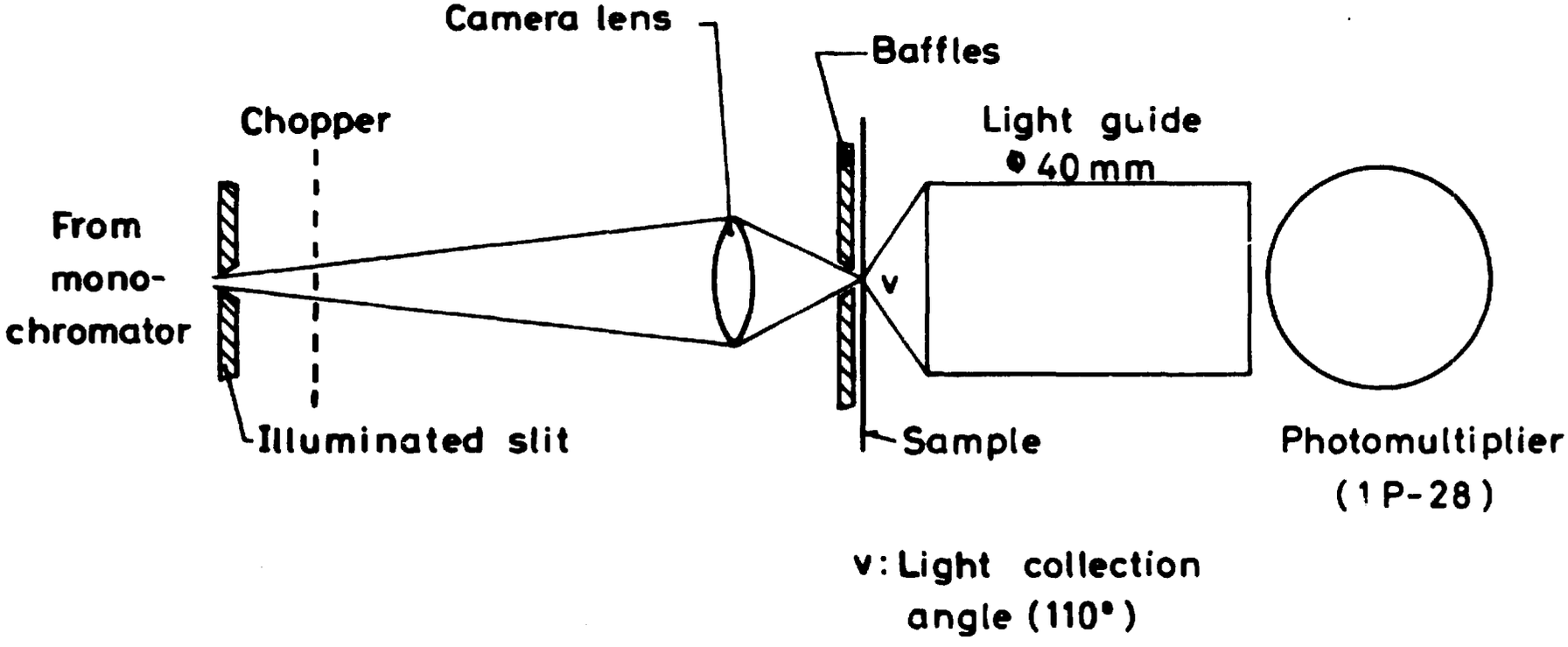


Fig. 3 Part of the optical system for transmittance measurement

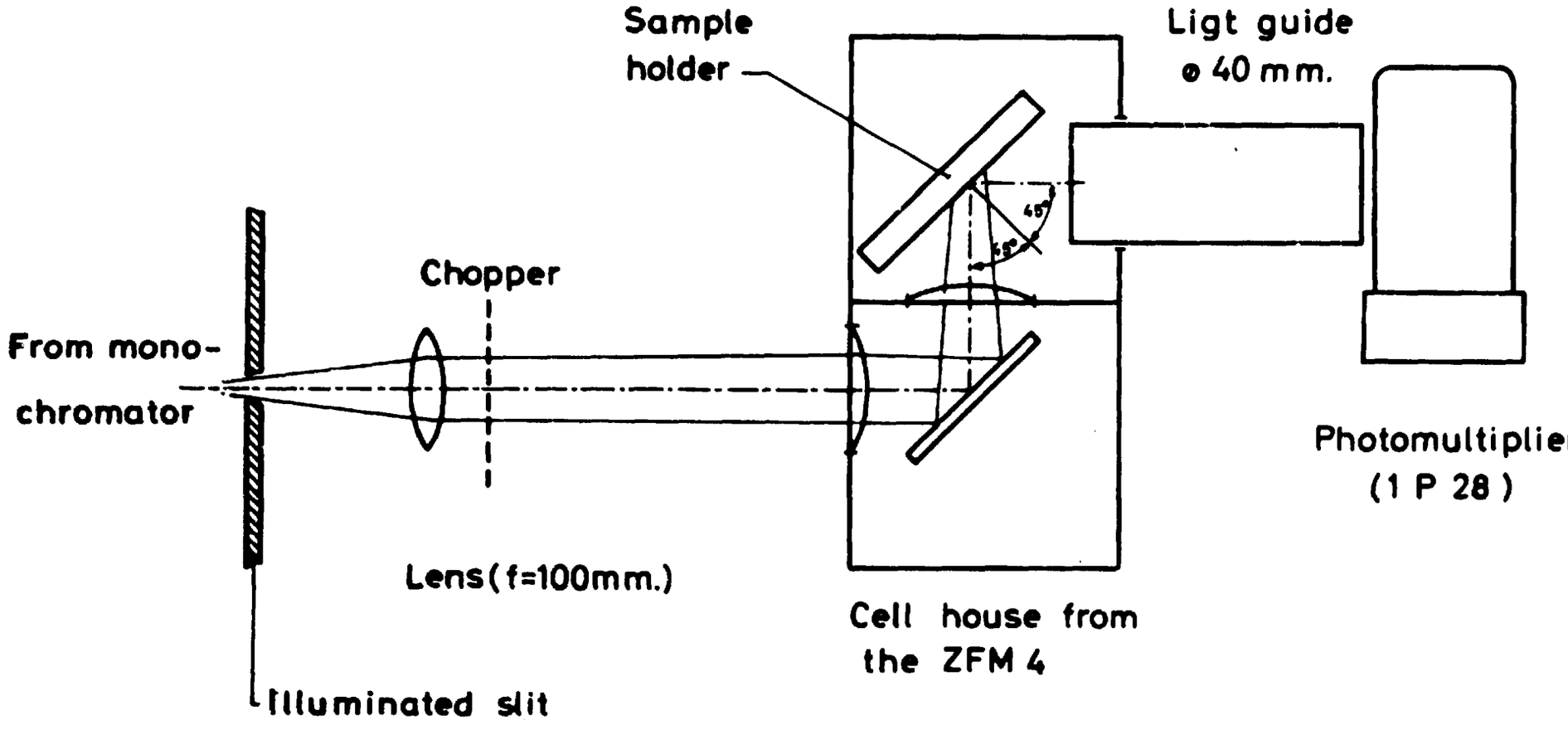


Fig.4 Part of the optical system for reflection measurement.

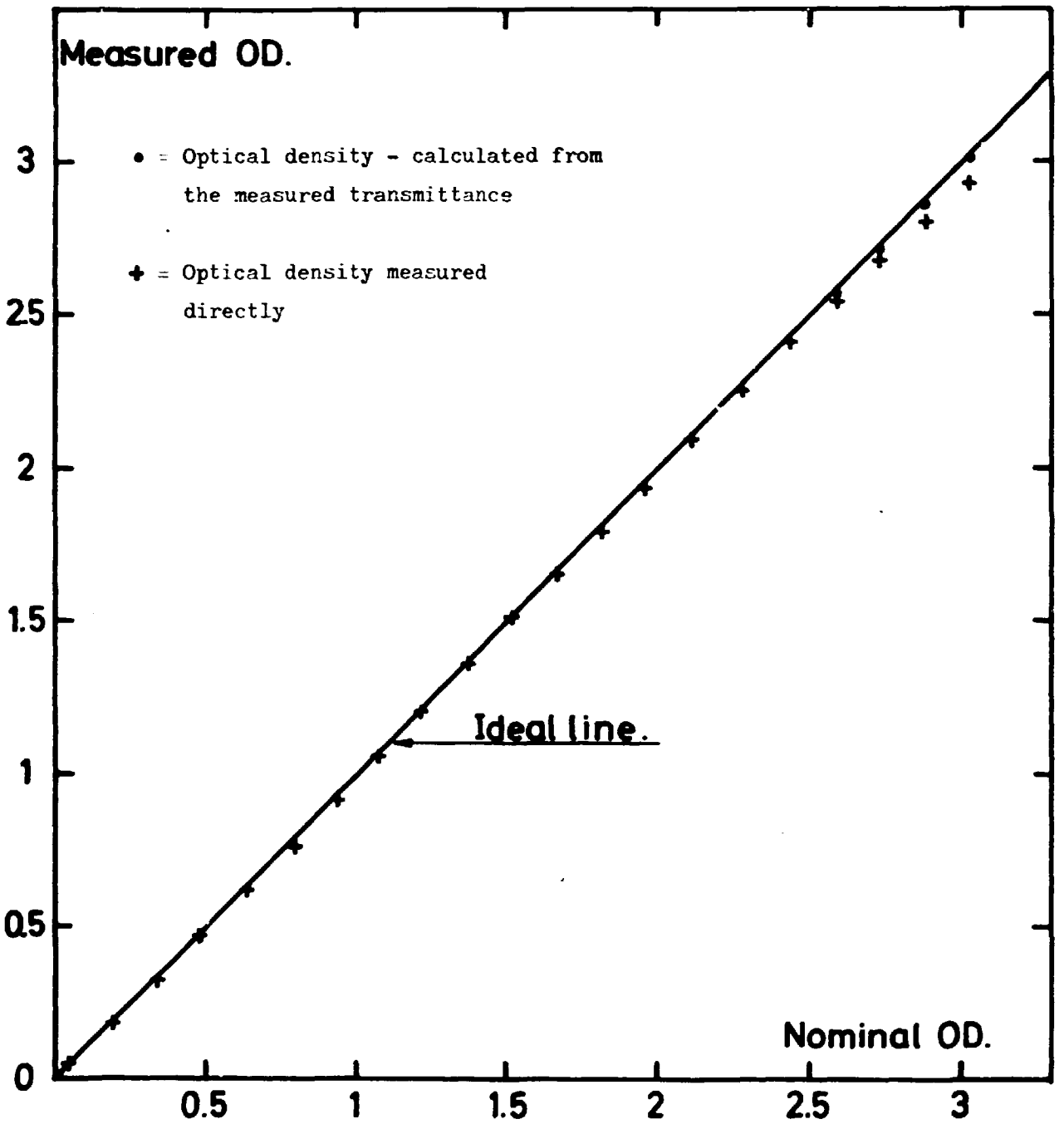


Fig.5 Linearity measurement.

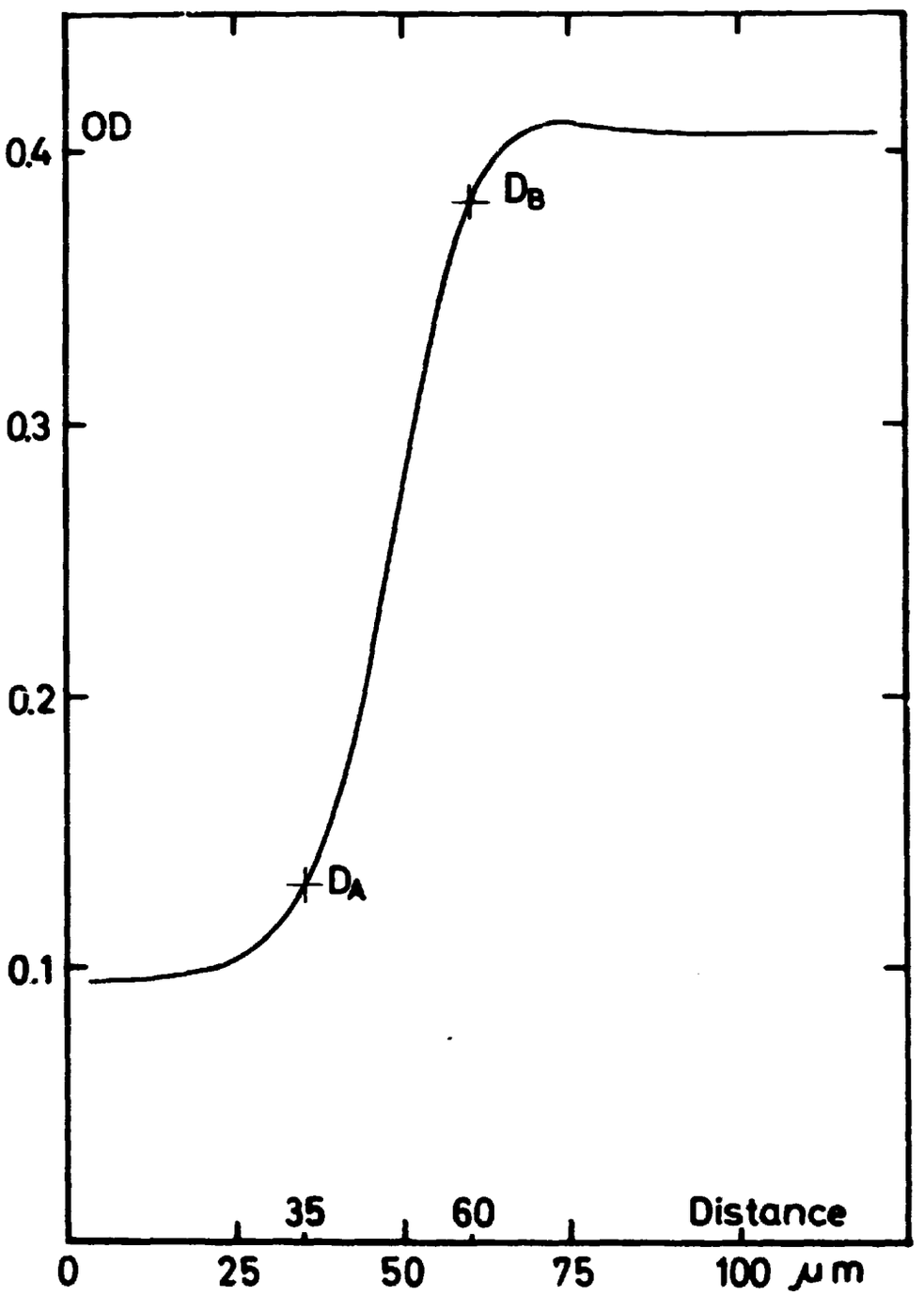


Fig.6 Knife-edge image response.

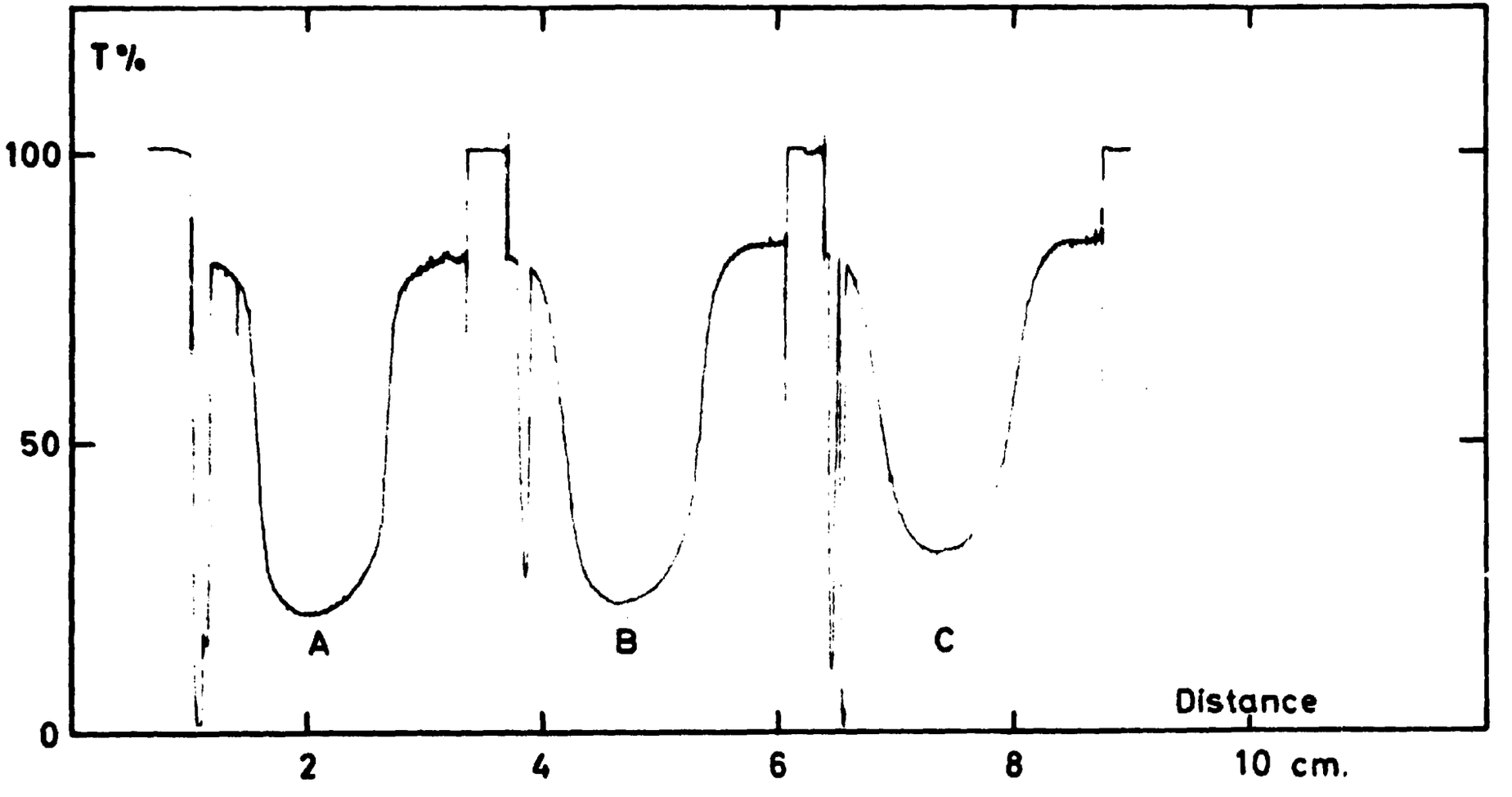


Fig. 7

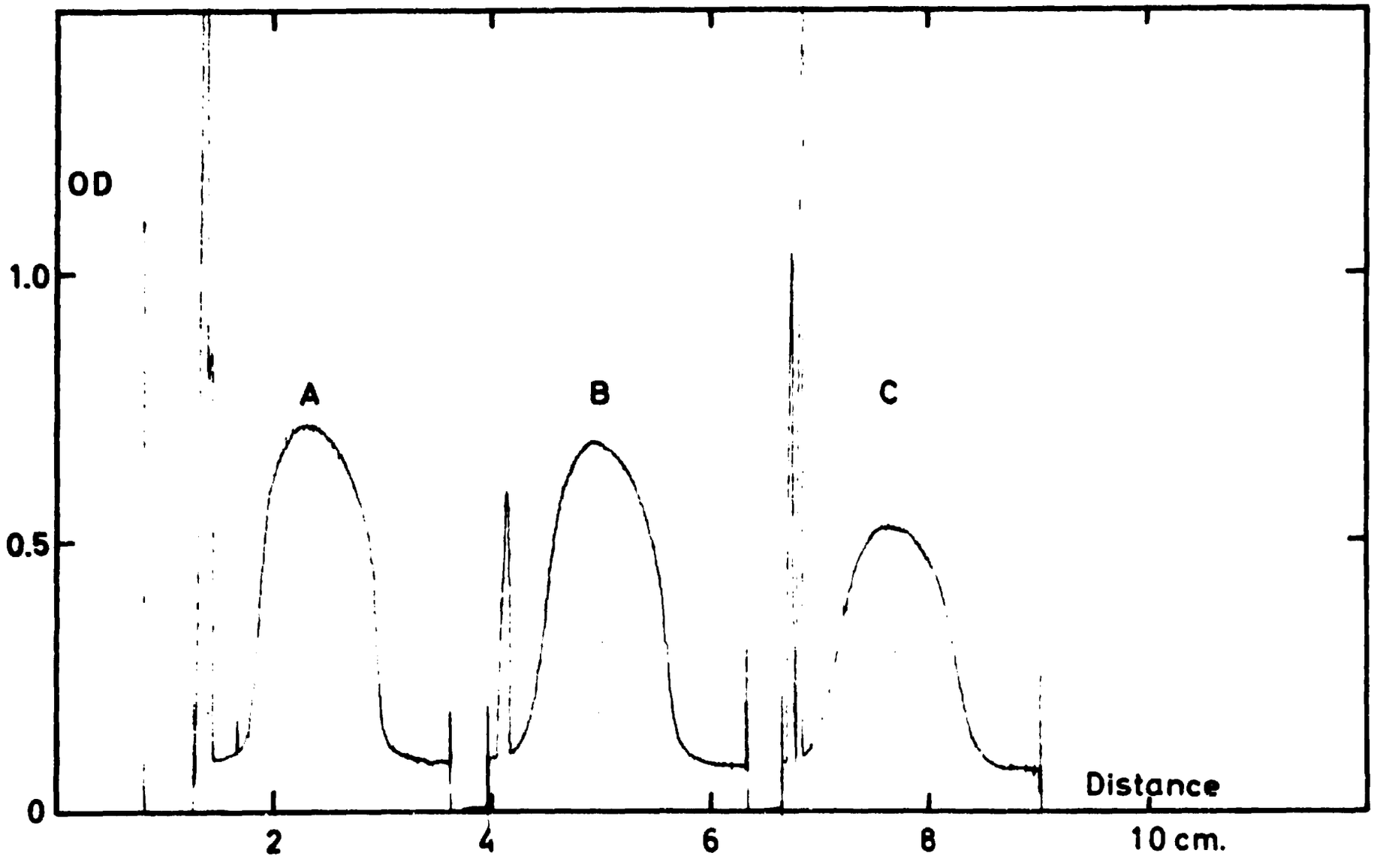
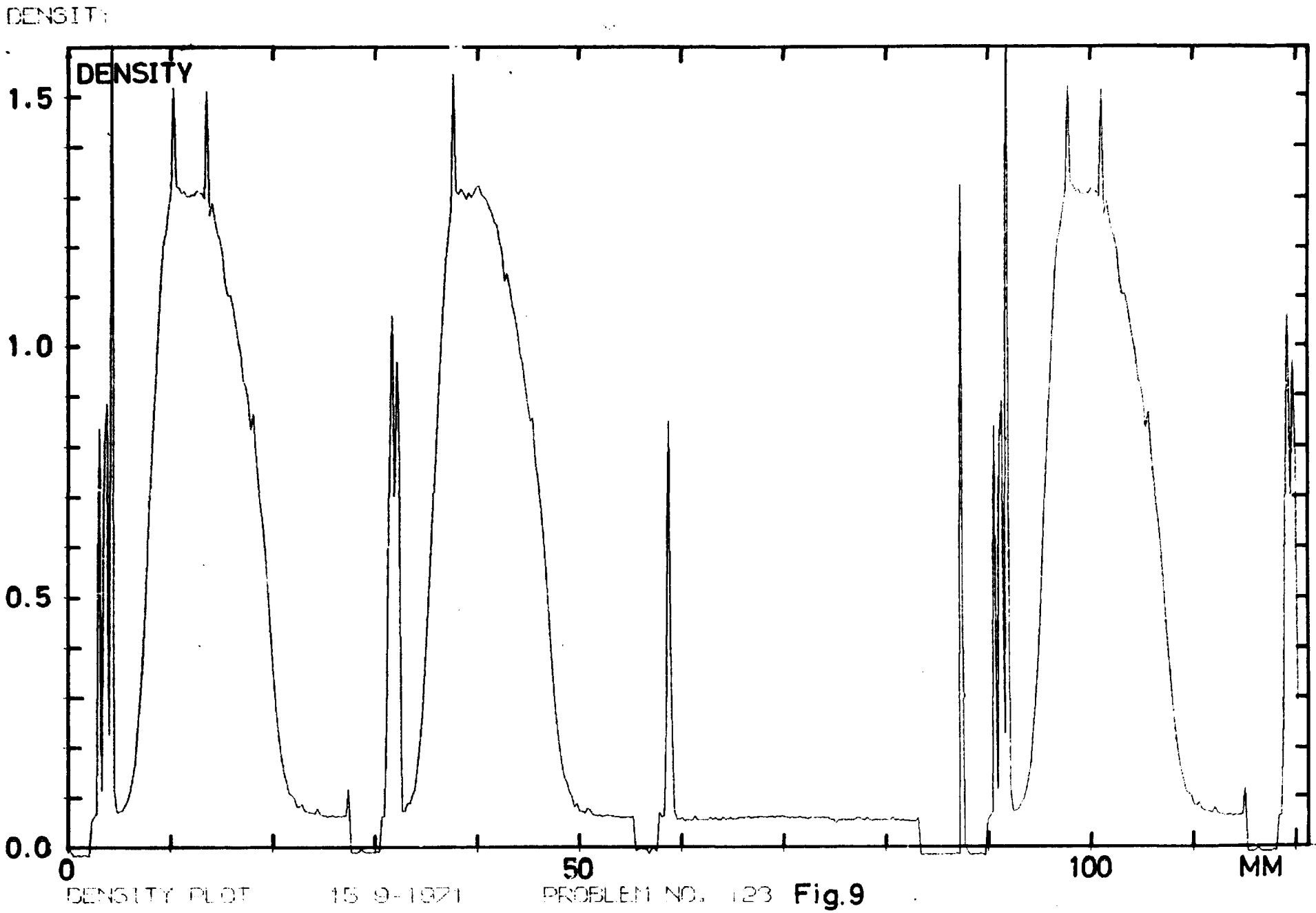


Fig. 8



DENSITY PLOT 15 9-1971 PROBLEM NO. 123 Fig.9